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ROTATIONAL STUDIES OF LATE-TYPE STARS. VII. M34 (NGC 1039) AND THE EVOLUTION OF ANGULAR MOMENTUM AND ACTIVITY IN YOUNG SOLAR-TYPE STARS

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ABSTRACT

We analyze Keck High Resolution Echelle Spectrometer (HIRES) observations of rotation and activity in F, G, and K dwarf members of the open cluster M34 (NGC 1039), which is 250 Myr old, and we compare them to the Pleiades, Hyades, and NGC 6475. The upper bound to rotation seen in M34 is about a factor of 2 lower than for the 100 Myr old Pleiades, but most M34 stars are well below this upper bound, and it is the overall convergence in rotation rates that is most striking. A few K dwarfs in M34 are still rapid rotators, suggesting that they have undergone core-envelope decoupling, followed by replenishment of surface angular momentum from an internal reservoir. Our comparison of rotation in these clusters indicates that the timescale for the coupling of the envelope to the core must be close to 100 Myr if decoupling does, in fact, occur.

Subject headings: open clusters and associations: individual (M34, NGC 1039) — stars: evolution — stars: late-type — stars: rotation

1. INTRODUCTION

M34 (NGC 1039) is an open cluster that is about 250 Myr old (Meynet, Mermilliod, & Maeder 1993; Jones & Prosser 1996). That makes it ideal for comparing to the Pleiades (age ~ 100 Myr; Patenaude 1978; Meynet, Mermilliod, & Maeder 1993; Basri, Marcy, & Graham 1996) and Hyades (600 Myr; Patenaude 1978; Torres, Stefanik, & Latham 1997). Such a comparison is especially interesting for solar-type stars, which undergo much change over that age interval. Solar-type stars (by which we mean roughly F7 V to K2 V) reach the zero-age main sequence (ZAMS) rotating at a variety of rates, from roughly solar on up to ~ 100 times solar, as seen in the Pleiades (Stauffer & Hartmann 1987; Soderblom et al. 1993, hereafter Paper IV), for example. Yet almost no spread in rotation exists among the solar-type stars of the Hyades (Radick et al. 1987; Paper IV). Chromospheric emission (CE), being intimately related to rotation, exhibits similar differences between these clusters (Paper IV).

The differences in rotation seen between the Pleiades and Hyades are believed to be an evolutionary effect. The paradigm is that rotation and convection interact in stars such as the Sun to generate a magnetic field. One manifestation of those fields is CE. The magnetic field can grip an ionized stellar wind well beyond the surface of the star, leading to angular momentum loss. In this picture, a rapidly rotating star generates a stronger magnetic field than a slowly rotating star, leading to a stronger field, more CE, and more rapid angular momentum (AM) loss. Thus rotation rates among a coeval population may start out very different but should converge with time.

There is more than one way, however, for a fast-rotating star in the Pleiades to end up looking like a slowly rotating star in the Hyades. For example, we can suppose that stars always rotate as solid bodies, forcing the entire star to spin down as AM is lost. An alternative hypothesis is that ZAMS stars may rotate at different rates in their convective envelopes and radiative cores (Stauffer & Hartmann 1987). The envelope has a relatively large radius but little mass, so spinning it down takes less time than it would to decelerate the entire star. The core, however, contains most of the AM and acts as a reservoir that can replenish the surface rotation for an extended time. In this case the surface rotation rate (and the spread in rates among a group of stars) will depend on the AM loss rate of the envelope, as well as on the coupling timescale between the core and the envelope. A coupling timescale that is short compared to the timescale for envelope AM loss is essentially the same as solid-body rotation.

Models for these two scenarios have been put forth by Li & Collier Cameron (1993) and Collier Cameron & Li (1994), and the essential difference between the two cases is as just described: if solid-body rotation pertains, then all the stars in the Pleiades will lose AM, and a sample of such stars will be seen to gradually converge in its distribution of angular velocity (Ω). If the core and envelope decouple, however, then the surface rates of some stars can stay high for an extended period as they get replenished from the core, followed by overall spindown once solid-body rotation is established. In other words, core-envelope decoupling delays the start of the solid-body phase. Barnes, Sofia, & Pinsonneault (2001) show that an additional factor is needed to explain the existence of slowly rotating stars in clusters as young as the Pleiades, namely the timescale for coupling of the star to a disk in the pre–main-sequence (PMS) phase. This adds another parameter to the models, but without it the distributions of rotation seen cannot be explained, with or without core-envelope decoupling.

TABLE 1

ROTATION AND ACTIVITY FOR STARS IN M34

JP	$(B-V)_0$	$T_{\rm eff}$	$v \sin i$ (km $\mathrm{s^{-1}}$)	$W_\lambda^{\rm em}$(Hα) (Å)	$W_\lambda^{\rm em}$(8498) (Å)	$F_{\rm H\alpha}$ (Mergs $\mathrm{cm^{-2}\ s^{-1}}$)	F_{8498} (Mergs $\mathrm{cm^{-2}\ s^{-1}}$)	log $R_{\rm H\alpha}$	log R_{8498}
17	0.46	6474	28.5	0.38	0.41	3.46	2.45	−4.46	−4.61
42	0.90	4870	7.4	0.14	0.10	0.46	0.27	−4.84	−5.08
51	0.37	6888	66.0	0.30	0.23	3.50	1.62	−4.56	−4.90
113	0.83	5079	11.7	0.29	0.15	1.09	0.45	−4.54	−4.93
133	0.62	5810	11	0.15	0.11	0.92	0.49	−4.85	−5.12
156a	0.44	6563	12.0	...	...	...	...	...	...
156b	0.49	6340	12.0	...	...	...	...	...	...
158	0.80	5173	45.0	0.66	0.44	2.70	1.38	−4.18	−4.47
172	1.08	4417	10.0	0.25	0.05	0.53	0.09	−4.61	−5.38
194	1.10	4373	8.0	0.33	0.06	0.68	0.10	−4.48	−5.32
199	0.80	5173	9.5	0.07	0.11	0.26	0.33	−5.19	−5.09
208	0.66	5658	≤ 7	0.14	0.11	0.77	0.45	−4.88	−5.11
213	0.54	6130	23.5	0.54	0.15	4.09	0.78	−4.29	−5.01
224	0.75	5338	13.3	0.14	0.02	0.63	0.05	−4.87	−5.93
227	0.76	5305	11.0	0.08	0.09	0.34	0.31	−5.11	−5.16
229	1.22	4144	8.2	0.57	0.10	0.91	0.14	−4.26	−5.08
246	0.42	6654	37.0	0.27	0.22	2.78	1.37	−4.60	−4.91
257a	0.47	6429	44.0	0.26	0.22	2.31	1.28	−4.62	−4.88
257b	0.47	6429	42.0	0.22	0.21	1.96	1.20	−4.69	−4.91
265	1.07	4438	34.0	1.11	0.49	2.46	0.91	−3.95	−4.38
268	1.14	4291	≤ 7	0.32	0.05	0.61	0.08	−4.50	−5.37
288	0.94	4759	≤ 7	0.24	0.07	0.70	0.16	−4.62	−5.26
289	0.90	4870	7.4	0.17	0.15	0.56	0.39	−4.76	−4.91
296	0.69	5548	≤ 7	0.08	0.00	0.39	0.00	−5.13	...
298	0.92	4814	8.9	0.20	0.17	0.63	0.41	−4.68	−4.87
305	0.46	6474	26.0	0.15	0.09	1.34	0.55	−4.87	−5.26
317a	0.64	5740	≤ 7	...	...	...	...	...	...
317b	0.71	5490	9.8	...	...	...	...	...	...
320	0.73	5407	12	0.24	0.17	1.13	0.59	−4.63	−4.92
329	0.40	6747	35.0	0.24	0.22	2.58	1.46	−4.66	−4.91
331	0.57	6007	18.9	0.12	0.17	0.84	0.82	−4.95	−4.96
356	1.11	4352	15.4	1.53	0.43	3.10	0.74	−3.82	−4.44
366	0.65	5695	≤ 7	0.12	0.10	0.72	0.40	−4.92	−5.17
377	0.84	5048	11.1	0.56	0.30	2.06	0.85	−4.25	−4.63
392	0.95	4732	8.4	0.14	0.06	0.39	0.14	−4.86	−5.31
397	0.81	5141	8.3	0.15	0.12	0.61	0.36	−4.81	−5.04
404	0.46	6474	17.0	0.11	0.08	1.00	0.49	−5.00	−5.31
415	0.72	5442	≤ 7	0.18	0.14	0.89	0.50	−4.74	−5.00
424	1.11	4352	23.3	2.02	0.35	4.10	0.60	−3.70	−4.53
425	1.02	4555	17.3	0.90	0.41	2.21	0.84	−4.04	−4.46
451	0.44	6563	42.0	0.34	0.16	3.34	0.98	−4.50	−5.03
482	0.99	4629	≤ 7	0.19	0.07	0.50	0.15	−4.72	−5.23
484	0.47	6429	21.5	0.17	0.05	1.51	0.30	−4.81	−5.51
489	0.89	4899	7.8	0.20	0.11	0.65	0.28	−4.70	−5.07
504	0.37	6888	25.0	0.16	0.14	1.89	0.96	−4.83	−5.12
515	0.57	6007	9.8	0.11	0.11	0.78	0.50	−4.98	−5.17
516	1.07	4438	11.2	0.20	0.08	0.44	0.15	−4.70	−5.17
536	1.01	4579	44.0	1.59	0.66	4.02	1.38	−3.79	−4.26
546	0.43	6609	15.5	0.20	0.15	1.98	0.94	−4.74	−5.06
570	0.85	5017	8.6	0.19	0.07	0.69	0.18	−4.72	−5.29

It may be possible to distinguish between these models with and without decoupling by looking at a cluster intermediate in age to the Pleiades and Hyades, so that we can see if such stars have changed their distributions of rotation rates. Such an effort was made in Paper V of this series (Soderblom & Mayor 1993), where rotation among stars of the Ursa Major Group was studied. After carefully considering membership for that kinematic group, there were not enough stars left for a meaningful comparison. More recently, James & Jeffries (1997) obtained rotation rates for some stars in NGC 6475, a cluster that is about 220 Myr old. Their results, shown below, reveal some fast rotators at that age, but their sample is too small, especially for G and K dwarfs, to provide a useful comparison to the Pleiades, and as they note, their sample was X-ray selected and is therefore biased toward rapid rotators.

M34, at an age of 250 Myr, is well suited for such a study of rotation in young solar-type stars. It is fairly rich, and it is close enough to make its solar-type stars accessible to high-resolution spectroscopy with the Keck telescope and its High Resolution Echelle Spectrometer (HIRES). This paper will illustrate how rotation and CE behave among a 250 Myr old group of stars and what that may mean for AM evolution among stars such as the Sun.

2. OBSERVATIONS AND ANALYSIS

We began this program at the Lick 3 m Shane telescope, using the Hamilton spectrograph (Vogt 1987), which records echelle spectra on a TI 800 × 800 CCD at a resolving power of about 50,000. We attempted to repeat in M34 what we had done in the Pleiades (Paper IV) for G dwarfs, but we had consistently bad luck with observing conditions. The result was low signal-to-noise spectra of some of the earlier spectral types in which we are interested, mostly mid- to late-F dwarfs. These spectra were reduced in the same way as the Hamilton spectra described in Paper IV.

Our primary interest, however, is in the G and K dwarfs of M34, for it is among those stars that we hoped to find some ultrafast rotators (UFRs), i.e., stars with $v \sin i \gtrsim 20$ km s^{-1}. Such stars are found in the Pleiades and α Persei clusters, but not in the Hyades. Just finding a few of them in M34 would constrain AM loss models. Also, we wished to study CE by examining Hα and the Ca II infrared triplet (IRT), meaning that we required at least moderate signal-to-noise ration (S/N).

This led us to observe M34 members with the HIRES (Vogt 1992) on the Keck telescope. Targets were chosen from the membership study of Jones & Prosser (1996), and range in $B-V$ from 0.44 to 1.29. The HIRES spectra included Hα, the Li λ6708 feature (which is reported on in Jones et al. 1997), and two of the three IRT lines (λ8498 and λ8662).

The detector for the Keck observations was a Tektronix 2048 × 2048 CCD having 24 μm pixels. We used the "C1" slit decker, which yielded a projected slit height of 7″ (36.6 pixels), and a projected slit width of 0″.86 (3 pixels), for a resolving power of 45,000. The wavelength range was about 6300–8700 Å, divided into 16 orders, with each order covering about 100 Å. This means the order coverage is incomplete. Integration times ranged from 5 to 40 minutes, and that gave a typical S/N of 70.

We obtained rotation ($v \sin i$) and radial velocity ($v_{\rm rad}$) measures by cross-correlating the spectra against narrow-lined templates, choosing a template with a temperature similar to the program star. Standard star spectra were also cross-correlated with spun-up templates, and the FWHM was measured. These procedures are described in Jones et al. (1997). The emission fluxes in the Hα and the 8498 Å line of the IRT were determined in the same way as in Paper IV, namely, by first subtracting the profile of an inactive star of the same intrinsic color (see Table 3 of Paper IV), measuring the equivalent width of the resultant emission feature, and then converting that W_λ to a flux. Finally, the fluxes were ratioed to the stellar bolometric flux to calculate $R_{\rm H\alpha}$ and R_{8498}. The appropriate formulae are given in Paper IV. Our results are listed in Table 1.

Some values in Table 1 differ from what was reported in Jones et al. (1997). First, in that paper we formally derived $v \sin i$ values as low as 5 km s^{-1}, but here we list any value below 7 km s^{-1} as "≤ 7" to be more conservative. Second, for three stars we could derive $v \sin i$ values for both components of spectroscopic binaries; these are JP 156, 257, and 317.

3. DISCUSSION

3.1. *Angular Momentum Loss after the ZAMS*

The essence of our observations of rotation in M34 stars is illustrated in Figure 1.

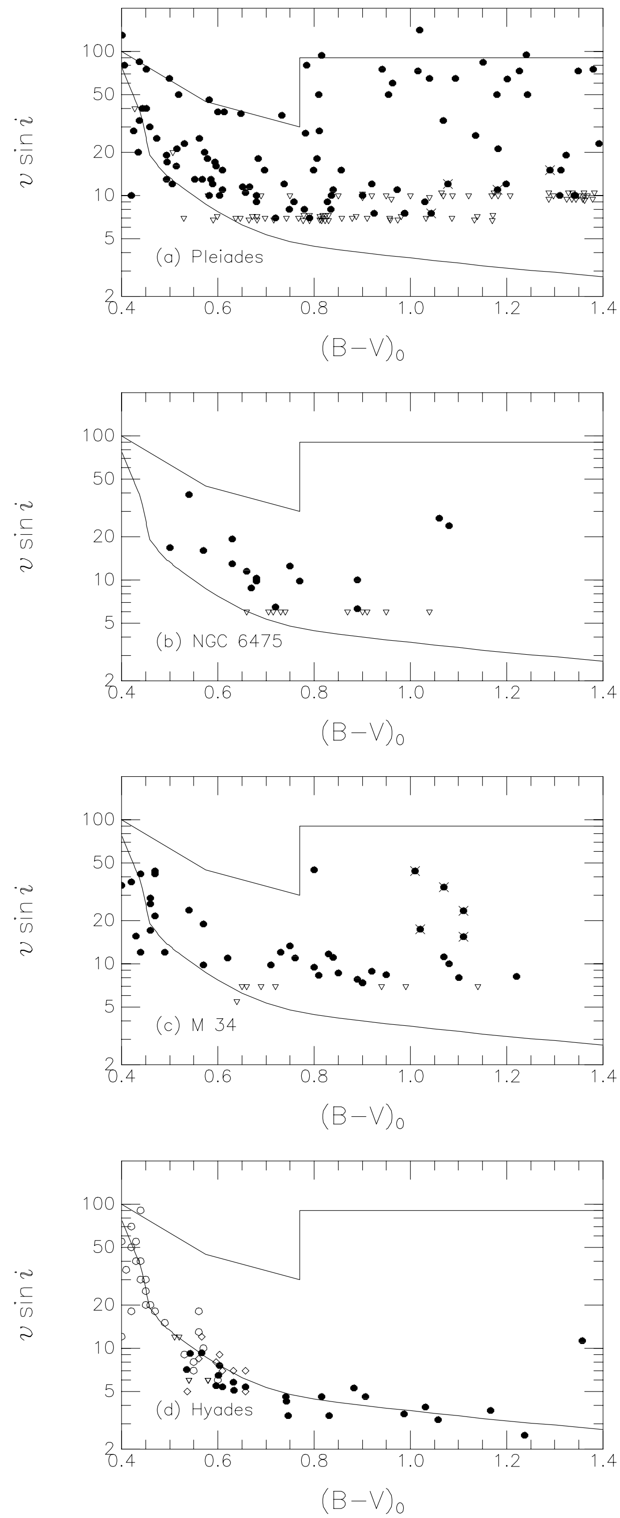

FIG. 1.—Rotation rate ($v \sin i$, in km s^{-1}) vs. dereddened $B-V$ for solar-type stars in four clusters. The upper line is meant to schematically outline the upper bound to rotation for the Pleiades. The lower line is a mean relation for the Hyades from Paper IV. (*a*) The Pleiades, 100 Myr old, from Paper IV. The triangles represent upper limits to $v \sin i$. (*b*) NGC 6475, 220 Myr old, from James & Jeffries (1997). (*c*) M34, at 250 Myr. There are four stars in the Pleiades and five in M34 that exhibit Hα emission that rises above the continuum, and their points are overlaid with crosses. (*d*) the Hyades, at 600 Myr. For the Hyades, the open symbols represent $v \sin i$ values, while the filled symbols are determined from observations of rotation periods, and so have no aspect dependence.

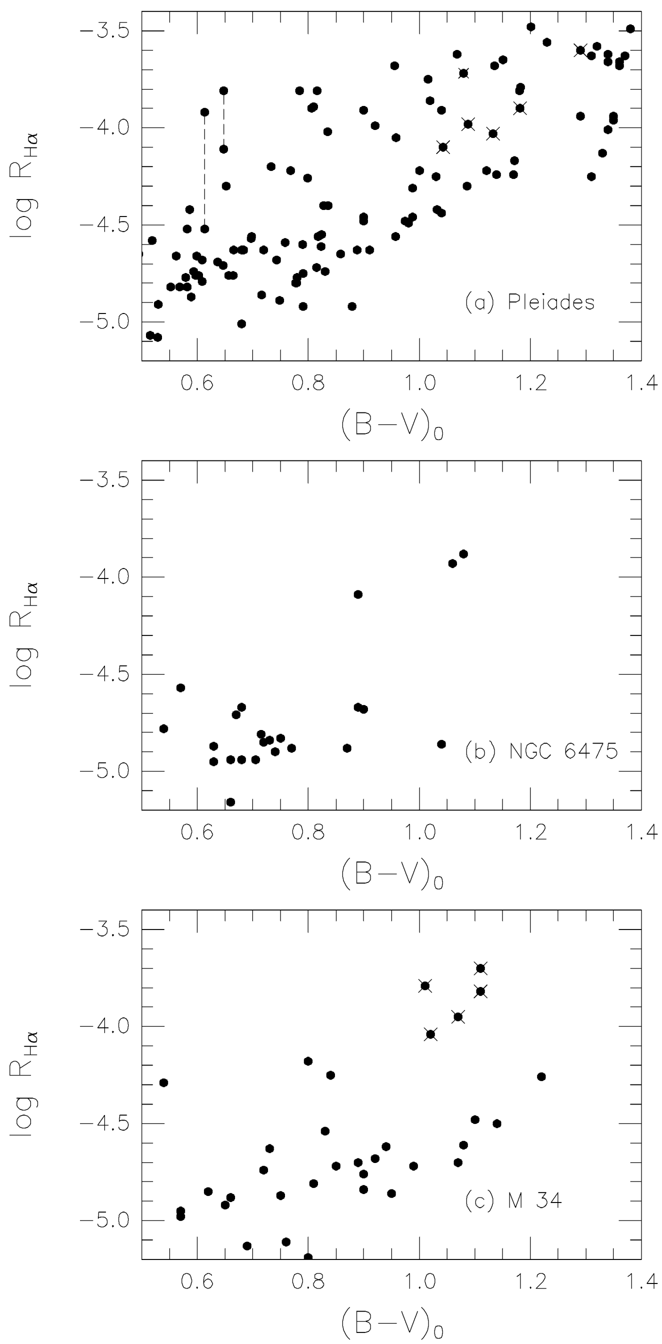

FIG. 2.—Normalized indices of Hα emission, $R_{H\alpha}$, vs. dereddened $B-V$ color for (*a*) the Pleiades (from Paper IV), (*b*) NGC 6475 (from James & Jeffries 1997), and (*c*) M34. The vertical dotted lines for two Pleiades stars connect maximum and minimum estimates of $R_{H\alpha}$ for those two stars because both show evidence of emission over the full breadth of the profile, not just in the core of Hα (see Paper IV). There are five stars in the Pleiades and five in M34 that exhibit Hα emission that rises above the continuum and their points are overlaid with crosses.

The first panel shows rotation in the Pleiades (Paper IV), to which two lines have been added. The upper curve represents the upper bound of the Pleiades distribution of rotation, while the lower curve is the mean of rotation in the Hyades (panel *d*, Paper IV). One key conclusion of Paper IV was that the rotation of solar-type stars, in evolving from the Pleiades to the Hyades, changes only modestly in the mean, but undergoes a huge convergence in rotation rates. Thus, at any one mass in the Pleiades, the rotation rates differ by an order of magnitude or more, yet in the Hyades, stars of the same mass have nearly identical rotation rates. This effect is shown here in $v \sin i$, but it has been confirmed through measurements of rotation periods (Radick et al. 1987; Prosser et al. 1993a, 1993b; Krishnamurthi et al. 1998).

Figure 1*b* shows the $v \sin i$ observations of James & Jeffries (1997) for NGC 6475 (220 Myr old). The presence of two stars with $v \sin i \approx 20$ km s^{-1} at $(B-V)_0 \approx 1.1$ suggests that rapid rotators exist at that age, but the small sample size precludes drawing more conclusions.

Figure 1*c* shows our results for M34. For the bluer stars [$(B-V)_0 \lesssim 0.7$], the rotation rates are similar to most Pleiads in this color range, except that the upper branch of the Pleiades rotational distribution (stars with $v \sin i \approx 50$ km s^{-1}) has disappeared. For the stars redder than 0.7 in $(B-V)_0$, few if any members of M34 have spun down to the low rates seen in the Hyades (represented by the lower line in each plot and shown in Fig. 1*d*). Many stars have $v \sin i$ values of about 8–15 km s^{-1}, essentially the same as seen in the Pleiades, but the upper envelope for M34 is about a factor of 2 lower than for the Pleiades (as represented by the upper line). Also, the proportion of rapid rotators in M34 (those with $v \sin i \gtrsim 15$ km s^{-1}) is the same as the proportion of UFRs (stars with $v \sin i \gtrsim 30$ km s^{-1}) seen in the Pleiades, given the sample sizes. Finally, M34 contains at least one blue UFR [JP 158, at $(B-V)_0 = 0.80$ and $v \sin i = 45$ km s^{-1}].

It is clear that the convergence in rotation rates exceeds any overall decrease in the average rotation rate as solar-type stars evolve from the age of the Pleiades to the age of M34 and on to the age of the Hyades. Stars that rotate relatively slowly at the age of the Pleiades will still be rotating at about the same rate much later. For example, Krishnamurthi et al. (1998) see Pleiades stars with rotation periods of 7–8 days at $(B-V)_0 \approx 1.1$, while at that same color Radick et al. (1987) observe rotation periods of 11–12 days in the Hyades, a change by a factor of about 1.5; our M34 $v \sin i$ values for the slow rotators are consistent with this trend. Yet in that same 500 Myr, the surface rotation rates of the UFRs have declined by a factor of 20 or more.

The calculations done so far to study AM loss in young solar-type stars have, of necessity, adopted the Pleiades and Hyades as being fully representative of any ensembles of stars of their ages. Yet the Pleiades and Hyades differ in one important respect (besides age): their metallicities. The Pleiades has near-solar abundances ([Fe/H] $= +0.06 \pm 0.05$; King et al. 2000), but the higher metallicity of the Hyades ([Fe/H] $= +0.127 \pm 0.022$; Boesgaard & Friel 1990) means that Hyads have deeper convective envelopes at a given mass. Other things being equal, this may lead to stars in the Hyades losing AM more quickly than solar-metallicity stars do. The importance of this can be gauged by pretending that a given Hyad acts like a solar-metallicity star of slightly lower mass. A comparison of the AM loss tracks of Collier Cameron & Li (1994) and the models of Sills, Pinsonneault, & Terndrup (2000) for different masses show that lower mass stars indeed lose AM more quickly, but the net difference is modest. In other words, there appears to be no valid reason to reject the Hyades as a basis of comparison for the observations.

3.2. *Activity in M34*

Figure 2 shows $R_{H\alpha}$ versus $B-V$ for stars in the Pleiades

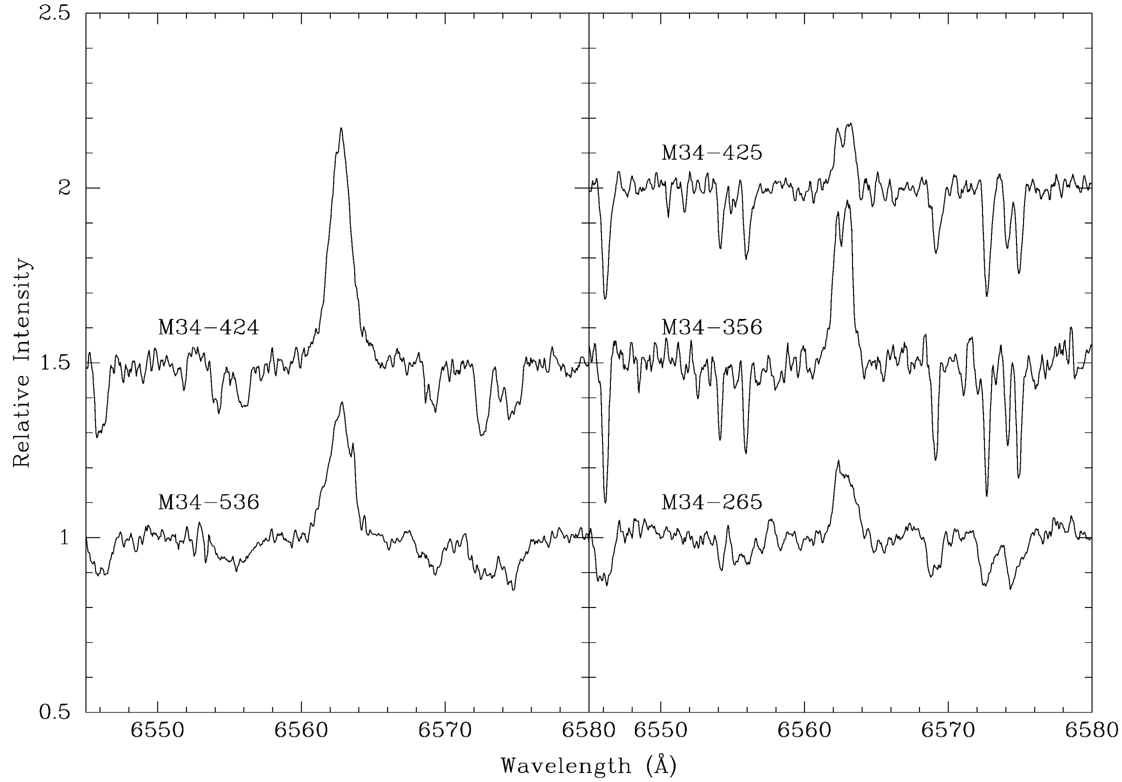

FIG. 3.—Hα profiles for five M34 stars with "overt" Hα emission, i.e., emission that rises above the continuum

(from Paper IV), NGC 6475 (James & Jeffries 1997), and M34. Among the M34 stars we observed, there are five that exhibit "overt" Hα emission; i.e., portions of the line rise above the continuum. These have been highlighted in Figure 2*c* with overlaid crosses, and their Hα profiles are shown in Figure 3.

In Paper IV we also showed six examples of Pleiades stars with overt Hα emission, and those shown in Figure 2*a* have also been highlighted.

Hα emission in M34 is similar to that seen in the Pleiades. All the M34 stars with $v \sin i > 15$ km s^{-1} and $B-V \geq 0.80$ show overt Hα emission, although few Pleiads above the same thresholds do. The lack of Pleiads with overt emission is probably not simply due to rotational broadening of the lines. This can be seen by noting that in the same color range of $B-V \approx 1.0$–1.1 there are M34 stars with overt emission having $v \sin i$ as great as Pleiads that lack overt emission.

Figure 4 compares the Pleiades and M34 with regard to the relation between Hα emission and a pseudo-Rossby number, $N'_{\rm R}$. The Rossby number is the ratio of a star's rotation period to its convective turnover time, the latter being calculated from models (see Paper IV). Only an upper limit to $P_{\rm rot}$ can be determined from $v \sin i$, of course, but that is sufficient here. The details of the calculation are given in Paper IV, equation (7).

At a given value of $N'_{\rm R}$, stars in M34 and the Pleiades have comparable levels of Hα emission overall. Any star can be moved to the right in this diagram, however, because the measured $v \sin i$ may not show the full extent of the true rotation ($v_{\rm eq}$). Within a cluster, those stars with the largest $v \sin i$ values are probably seen equator-on, so it is more likely that Pleiades stars with $\log N'_{\rm R}$ from -1.0 to -1.4 in fact have true $\log N'_{\rm R}$ values that are smaller (i.e., approaching -2) because those stars do not have the largest $v \sin i$ values seen in their color range.

Figure 5 shows a comparison of $R_{\rm H\alpha}$ to R_{8498} for M34 stars. As for the Pleiades (Paper IV), different chromospheric indices yield different pictures of the chromosphere, with scatter that exceeds observational error, but there is a broad correlation between the quantities.

One expects the stars with overt Hα to also emit strongly in X-rays. Simon (2000) has recently published *ROSAT* observations of M34, and of the five stars that emit in Hα, only two were detected by him. Of the remaining three, two (stars 265 and 356) would have been at the very edges of the *ROSAT* field (where the sensitivity is lower), but star 536 is only 12′ from the center of the field and so should have been detected. The small number of stars in common between our sample and Simon's prevents firm conclusions from being drawn, but it appears possible that not all strong Hα emitters are also strong in X-rays.

4. CORE-ENVELOPE DECOUPLING VERSUS SOLID-BODY ROTATION

It has been hypothesized that the surface AM of some stars is steadily replenished by an internal reservoir over time when they are young. Can we entirely rule out solid-body rotation? Collier Cameron & Li (1994) show calculations of the evolution of rotation when no decoupling occurs. In their Figure 3, the net change in Ω (the angular velocity) for the slow rotators in going from 100 to 250 Myr is only about 0.1 dex, an amount that may be undetectable in our observations of $v \sin i$. The rapid rotators in their models drop by about 0.3 dex in Ω over this time interval, just as we see them do. For the slow rotators, the change in the models going from 100 to 600 Myr is 0.3 dex, or a factor of 2. The actual change we see is comparable to this.

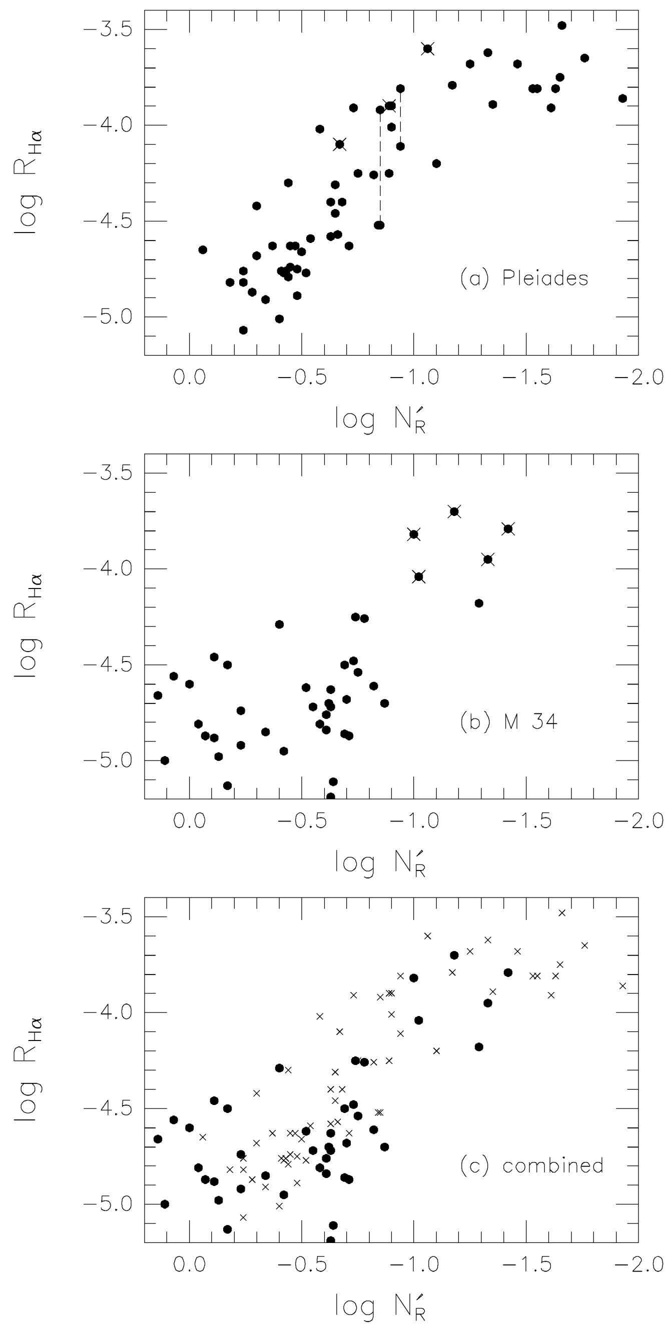

FIG. 4.—Normalized indices of Hα emission, $R_{H\alpha}$, vs. N'_R, the normalized $v \sin i$ equivalent to a Rossby number. For the Pleiades, upper limits to $v \sin i$ are not shown, and for both the Pleiades and M34 stars with overt Hα emission are highlighted. In the bottom panel, the solid points are for M34 and the crosses are for the Pleiades.

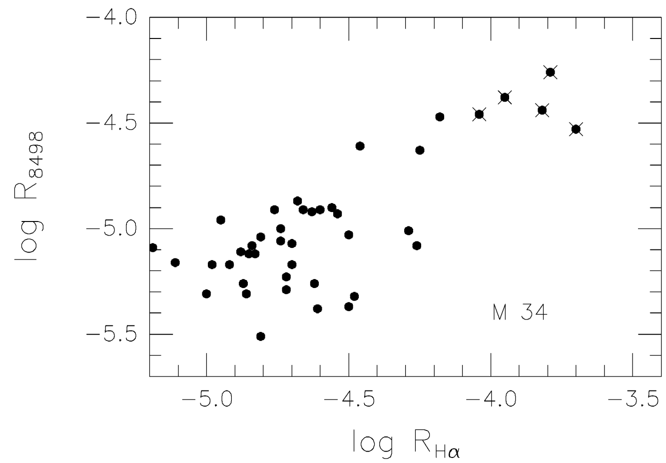

FIG. 5.—Normalized indices of Ca II IRT emission, R_{8498}, vs. $R_{H\alpha}$ for stars in M34. As expected, the two quantities are well correlated overall, but the correlation breaks down among the weak emitters.

If core-envelope decoupling occurs, its effects should be most evident at an intermediate age like that of M34 among stars that started as UFRs. By comparison, the slow rotators are probably spinning as solid bodies for the most part, and the very fastest rotators in the Pleiades must also be solid bodies because they already have extremely short periods (as little as 0.25 day): how much faster could a core be spinning? In M34 we see intermediate-level rotation rates at $B-V$ near 1.0, while the more massive stars have mostly converged to similar rates. Why do these K dwarfs still show appreciable surface rates? Either they are inherently less efficient at losing AM, which is contradicted by models, or they have tapped into an internal reservoir. It may be possible to construct models with solid-body rotation that match the observations better, but the easiest way to account for all the data is to invoke core-envelope decoupling. As we have pointed out before (Paper IV), core-envelope decoupling also helps to account for the strong mass dependence of rotation in solar-type stars by the way in which the ratio of the moment of inertia of the core to that of the envelope vary with mass. Observations of rotation periods for a significant sample of stars in a cluster about 200–300 Myr old will, we believe, settle this issue by showing just how slowly the slowest rotating stars spin.

Barnes, Sofia, & Pinsonneault (2001) also favor core-envelope decoupling in their models of disk locking in the early evolution of solar-type stars. They note that models with solid-body rotation require disk locking for 10–20 Myr. This is not impossible, but it is uncomfortably long when other observations suggest lifetimes for optically thick disks that are well under 10 Myr (Hollenbach, Yorke, & Johnstone 2000).

For the moment, assume that core-envelope decoupling indeed takes place in order to see what constraints we can place on the timescale for angular momentum transfer ($\tau_{\rm coupl}$) between the surface and the inner regions. First, we note that $\tau_{\rm coupl}$ cannot be much less than about 100 Myr, or otherwise core-envelope decoupling would never occur in the first place. This is because the PMS evolutionary timescales for low-mass stars can exceed 100 Myr, yet we see UFRs in those masses. At the same time, the near-uniformity of rotation rates seen in the Hyades, at an age of 600 Myr, suggests that several $\tau_{\rm coupl}$ have occurred in the 500 Myr from the Pleiades to the Hyades. If $\tau_{\rm coupl}$ were as much as 500–1000 Myr, then Hyades stars could not have achieved such uniform rotation rates, and if $\tau_{\rm coupl} \sim 2$ Gyr, then the Sun would not show solid-body rotation (unless it started as a slow rotator). All this means that $\tau_{\rm coupl}$ is unlikely to exceed 100 Myr by much, and so, to first order, if decoupling occurs then the recoupling timescale, $\tau_{\rm coupl}$, is ~ 100 Myr.

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